

Microengineering of Optical Properties of GeO₂ Glass by Ultrafast Laser Nanostructuring

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Nanostructuring in glass by ultrafast laser paves the way for integrated optics. In this paper, form birefringence induced by ultrafast laser direct writing in GeO₂ glass is systematically investigated. It is shown that the pulse energy for maximum retardance in GeO₂ glass is ≈65% lower than in fused silica. The induced retardance by laser scanning is two times higher than that by stationary irradiation under the same processing conditions. The optimum pulse duration for maximum retardance in GeO₂ glass lies within sub-picosecond region, i.e., typically around 500 fs, while in fused silica it is in the picosecond regime at around 1–2 ps. A reversed polarization dependence of retardance at low pulse densities and low pulse repetition rates is observed in GeO₂ glass. As a result, two optical applications including a radial polarization vortex converter and a computer-generated hologram are demonstrated in GeO₂ glass by spatial manipulation of the optical axis of the locally induced form birefringence. The microengineering of optical properties of GeO₂ glass by ultrafast laser direct writing may lead to new applications in near-/mid-infrared optics.

1. Introduction

Ultrafast laser micromachining of transparent materials has attracted tremendous interests during the past two decades due to its ability to achieve internal three-dimensional fabrication with resolution of up to sub 100 nm.^[1,2] Due to the complexity of nonlinear processes taking part during

the femtosecond laser interaction with transparent materials, e.g., silica glass in particular, several different types of modification including isotropic refractive index change,^[3] self-assembled nanogratings,^[4] and microvoids^[5] have been reported depending on the processing conditions. The self-organized nanogratings are most attractive for their unique properties including anisotropic light scattering,^[6] chemical etching selectivity,^[7,8] and form birefringence with a high stability at elevated temperatures.^[9] Recently, nanogratings in silica glass were successfully harnessed in several important applications such as micro/nanofluidic devices,^[10,11] polarization sensitive optical elements,^[12] 5D optical data storage.^[13,14] Meanwhile, numerous efforts have been taken to investigate the formation mechanism of nanogratings by different research groups. Physical models such as interference of bulk electron plasma waves with the incident light,^[4] asymmetrical evolution of nanoplasmas,^[15,16] and interference of self-trapping of exciton–polaritons^[17,18] have been proposed to be responsible for nanograting formation.

More recently, the formation of femtosecond laser-induced nanogratings has been confirmed in various glasses other than fused silica including GeO₂ glass,^[19–21] binary titanium silicate glass,^[22] borosilicate glasses,^[22,23] niobium silicate glass,^[24] highly porous glass,^[25] and aluminoborosilicate glass.^[26] Lancry et al.^[27] revealed that porous nanoplanes can be formed not only in silicate glasses with anomalous density behavior with fictive temperature, but also within glassy systems with normal density behavior. However, except for pure GeO₂ glass, nanogratings formation in other glasses requires extremely rigorous parameters and the induced birefringence is usually much weaker than in fused silica. The drawbacks may hinder practical applications of nanogratings in those glasses. As for GeO₂ glass, it has been demonstrated that the parameter window for nanograting formation and the induced birefringence are comparable to or even more superior than fused silica, which could ensure better performance of fabricated microdevices. In addition, GeO₂ glass exhibits higher transparency in the mid-infrared region and a higher nonlinearity as compared to fused silica,^[28,29] which promises novel applications in the near-/mid-infrared region. Nevertheless, much fewer attempts have been carried out on implementing

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the femtosecond laser induced form birefringence in GeO_2 glass.

In this letter, the birefringence with polarization dependent slow axis induced by ultrafast laser in GeO_2 glass and the effects of various parameters are systematically investigated. It is revealed that the retardance induced by laser scanning is two times higher than that by stationary irradiation. Formation threshold of form birefringence and its relation to pulse duration under certain focusing conditions is experimentally explored. A reversed polarization dependence of form birefringence as compared to fused silica, which is repetition rate related, is observed in GeO_2 glass. Here we also demonstrate various form birefringence based optical element designs including a radial polarization vortex converter and a computer generated hologram successfully imprinted in GeO_2 glass.

2. Results and Discussion

Femtosecond laser modification of transparent materials can be performed in stationary irradiation (dots) or in scanning mode (lines). In previous work reported by Asai et al.,^[21] the nanogratings and structure evolution in GeO_2 glass induced by stationary irradiation was studied. It should be noted that a large number (2.5×10^6) of pulses was delivered in each spot while the induced retardance was relatively small i.e., less than 100 nm. This phenomenon raises a discussion whether the form birefringences induced by stationary irradiation and by scanning are the same. To move this further, we quantitatively compare the retardance induced in both modification regimes.

Figure 1 shows a set of dots and a corresponding set of lines imprinted with pulse energy varying from 30 to 600 nJ (from right to left) and same pulse density of 2500 pulses

per dot for dots and 2500 pulses μm^{-1} for lines. It should be noted that in the optical microscope image (Figure 1a) the light intensity transmitted by the dots is lower than that transmitted by the lines, indicating the higher scattering caused by the induced structures by static irradiation. In addition, the side view images revealed that dots consist of several separated dark regions along the laser propagation direction while the structure of the lines along the laser propagation direction is dominated by visually more continuous and bright modification. The separated dark regions could be caused by inhomogeneous distribution of laser intensity along the propagation direction close to the focus, which is similar to the generation of void chains reported in other transparent materials.^[30,31] The imprinted elements were further characterized by the quantitative birefringence measurement system (CRi Abrio, Olympus BX51), which allows measurement of the absolute value of the retardance (Figure 1b) and mapping of the slow axis orientation (Figure S1, Supporting Information). It is revealed that the slow axis of the induced birefringence is always perpendicular to the laser polarization direction (Figure S1, Supporting Information) regardless of the applied pulse energy, which manifests itself as form birefringence originated from formation of nanogratings.^[13,21] Under the same processing conditions, the induced retardance in lines is approximately two times stronger, which is further confirmed by quantifying the induced retardance as shown in Figure 1c. The analysis of retardance indicates that the anisotropic microstructure formed by the laser scanning is more uniform than that formed by static irradiation under the same parameters. The difference is most likely to be caused by the translation of the beam focus. In dynamic writing, the front part of the laser beam preheats the unmodified front side along the scanning direction and preseeded some defects that can enhance anisotropic microstructure e.g., nanograting formation, while

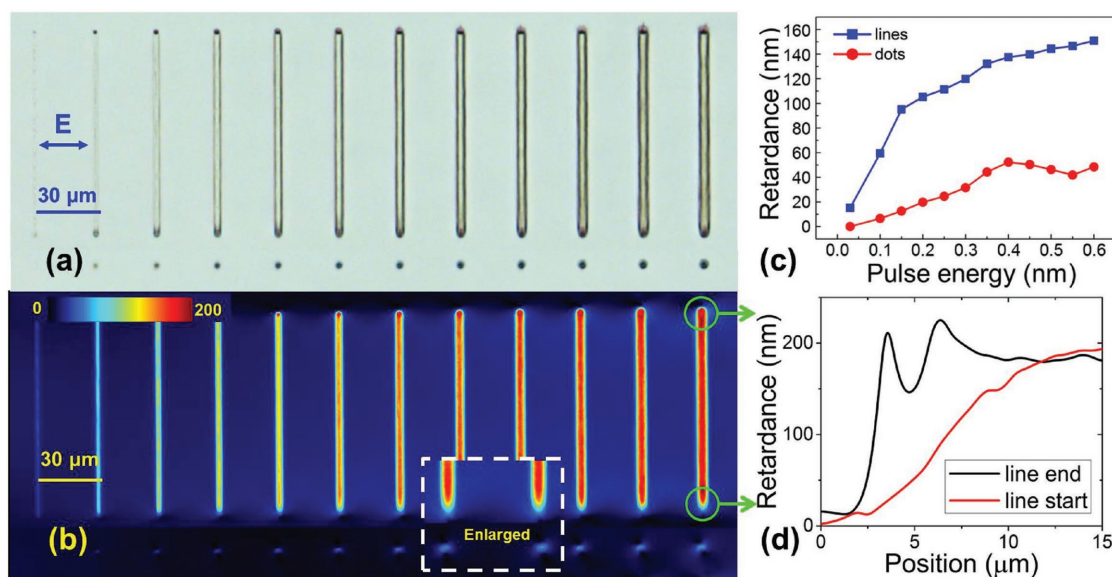


Figure 1. a) Natural light optical microscope image, b) quantitative retardance microscopy image, c) retardance as a function of pulse energy of dots and lines imprinted at pulse densities of 2500 pulses per dot and 2500 pulses μm^{-1} in GeO_2 glass, and d) the retardance profiles of line start and line end. Repetition rate is 25 kHz, pulse duration is fixed at 600 fs, the slow axis azimuth is the same and in the direction perpendicular to laser polarization. Insertion shows the enlarged dots and beginning of the lines.

the rear part of laser beam could give an extra effect on the modification at the frontier and incubates the formation of nanogratings when it passes by. This process is continuous in the dynamic writing, providing a more uniform distribution of energy along the writing direction. However, the energy distribution during anisotropic microstructure formation in static case is governed by the Gaussian distribution leading to a less uniform structure. The proposed mechanism is partially evidenced by the start of the lines (insertion in Figure 1b) and the retardance profile of the line start along writing direction (Figure 1d), indicating the transition between static irradiation and dynamic writing. Two peaks are observed in the retardance profile of line end, which can be ascribed to the formation of void-like structure at the end of lines.^[25]

In order to optimize the laser parameters for the induction of higher birefringence by laser scanning in GeO₂ glass, dependence of retardance on different combinations of pulse duration and pulse energy was studied for GeO₂ glass as well as for fused silica at a fixed pulse density of 1000 pulses μm^{-1} and a repetition rate of 200 kHz (Figure 2). It was observed that within the same processing parameters, the induced maximum retardance values for the two glasses are similar. However, the pulse energy required to achieve maximum retardance of around 150 nm in GeO₂ glass (at ≈ 200 nJ) is lower than that in fused silica

(at 500–600 nJ), which makes it possible to obtain nanogratings of better resolution and higher quality when less energy is deposited into the glass. More importantly, the optimum pulse duration for maximum retardance in GeO₂ glass lies within sub-picosecond region (typically 500 fs, $E // v$) while in fused silica it lies in the picosecond region (typically 2 ps, $E // v$), which means higher birefringence could be obtained in GeO₂ glass with femtosecond pulses. In addition, a strong dependence of retardance on laser polarization direction is revealed. The retardance plots extracted from the set of scanned lines under the pulse density of 1000 pulses μm^{-1} show that the laser polarization parallel to the scanning direction ($E // v$) gives higher retardance than the polarization perpendicular to the scanning direction ($E \perp v$) (Figure 2), which is in agreement with the previous observations reported by Gecevicius et al.^[32] Moreover, it is also apparent that formation threshold of form birefringence in GeO₂ glass is around two times lower than in fused silica, which may be associated with difference of the band-gaps of the two glasses i.e., ≈ 4 eV for GeO₂ glass and ≈ 9 eV for fused silica. The Keldysh parameter γ calculated with the setting of parameters is beyond 1.5, indicating that multiphoton ionization is dominant during form birefringence formation near threshold. Thus, a four-photon process for GeO₂ glass and an eight-photon process for fused silica would be expected

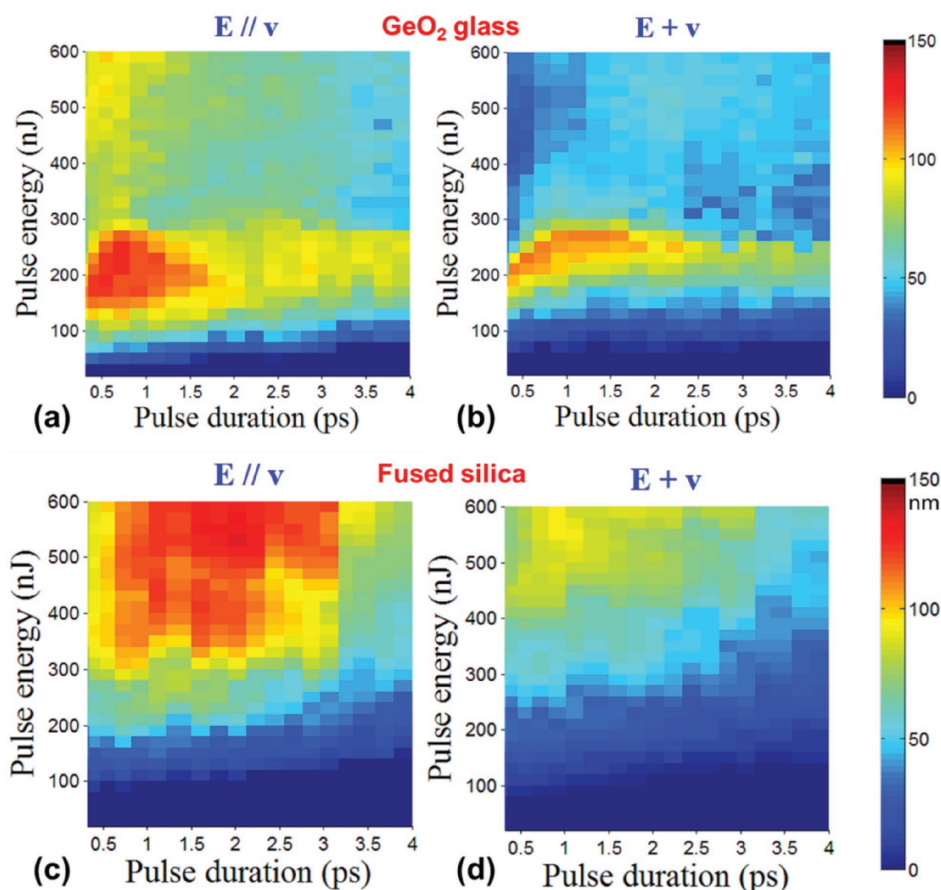


Figure 2. Pseudo color plots of retardance induced by scanning the laser beam in two polarization states (" $//$ " for parallel, " $\perp$ " for perpendicular to scanning direction) as a function of pulse energy and number of pulses for a,b) GeO₂ glass and c,d) fused silica. Parameters: Pulse repetition rate is 200 kHz and the pulse density is 1000 pulses μm^{-1} .

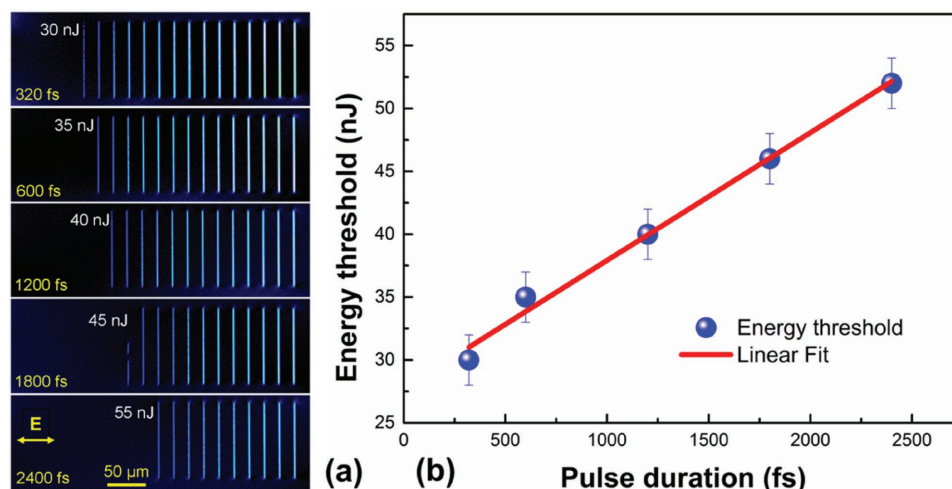


Figure 3. a) Quantitative birefringence microscopy image of lines imprinted by pulses of various pulse durations with pulse energy from 10 to 100 nJ and b) dependence of nanograting threshold on pulse duration for GeO₂ glass. Repetition rate is 200 kHz, pulse density is 1000 pulses μm^{-1} .

triggering form birefringence formation, leading to a different threshold.

For the further studies of the formation threshold of the form birefringence and its relation to pulse duration, lines imprinted with pulse energy varying from 10 to 100 nJ at various pulse durations were analyzed by the quantitative birefringence measurement system. The retardance image of the lines (Figure 3a) shows that the minimum pulse energy sufficient to induce retardance in GeO₂ glass is of several tens of nanojoules, and is dependent on the pulse duration, i.e., the amount of energy necessary for form birefringence formation increases with increasing the pulse duration with a focusing lens of 0.55 numerical aperture (N.A.). The minimum pulse energies at which retardance arises were regarded as energy threshold for form birefringence formation by different pulse durations, which were plotted in Figure 3b. The energy threshold exhibits a linear increase as a function of pulse duration, indicating nonlinear processes triggering the formation of form birefringence, which needs to be further clarified by sophisticated experiments and calculations, what is out of the scope of this paper.

It is well known that the repetition rate of femtosecond pulses is one of the key parameters that can affect the formation of form birefringence in glass. Previous studies have shown that the window of parameters for form birefringence formation in fused silica is significantly narrowed down at higher repetition rates due to the presence of heat accumulation effect.^[33,34] In addition, Corbari et al. noticed a reverse on the dependence of retardance on polarization direction as repetition rate increases when processing with 600 fs pulses at a fix pulse density.^[35] To get better control of induced birefringence in GeO₂ glass for practical applications, evolution of retardance as a function of pulse density as well as pulse energy at various repetition rates was analyzed, as shown in Figure 4. The growth trends of retardance with respect to pulse density under all repetition rates are similar and saturated at a pulse density of ≈ 2000 pulses μm^{-1} . The saturated retardance decreases with increasing repetition

rate, and the difference is enlarged above 200 kHz, in accordance to previous observations.^[34] Surprisingly, the transition of dependence of retardance on polarization direction is observed at 200 and 500 kHz (Figure 4d,e), and a totally reversed polarization dependence of retardance is observed for lower repetition rates, i.e., ≤ 100 kHz (Figure 4a–c). For 200 and 500 kHz, the induced retardance in parallel polarization configuration is higher than that in perpendicular polarization configuration at a relatively low pulse density before the saturation. However, the dependence of retardance on polarization is reversed when it reaches saturation at higher pulse densities. For lower repetition rates (≤ 100 kHz), the induced retardance in perpendicular polarization case is always higher than in parallel polarization case, which is against the explanation based on the effect of the polarization dependent Fresnel reflection at the boundaries of an induced structure.^[36]

It is also worth noticing that the dependence of retardance on pulse energy changes with repetition rate (Figure 4f). At an optimized pulse density of 2500 pulse μm^{-1} , the retardance induced at 25 and 50 kHz increases monotonously with the pulse energy increase in the window of 50–800 nJ. When the repetition rate is increased to 100 kHz and higher, the induced retardance increases firstly and then decreases with the increasing pulse energy, which can be assigned to the material thermal heating at larger pulse energies. These results indicate that the induced birefringence can be manipulated in a relatively wide range of energies with the femtosecond pulses operating at low repetition rates.

Taking the form birefringence as an advantageous property of nanogratings induced in fused silica and other transparent materials such as semiconductor thin films have been exploited for various applications.^[12,37] Here we demonstrate that geometric phase optical elements, including a space variant polarization converter and a computer-generated hologram with phase gradients reaching up to ≈ 1 rad μm^{-1} , can be realized in GeO₂ glass by manipulating the slow axis of the induced form birefringence.

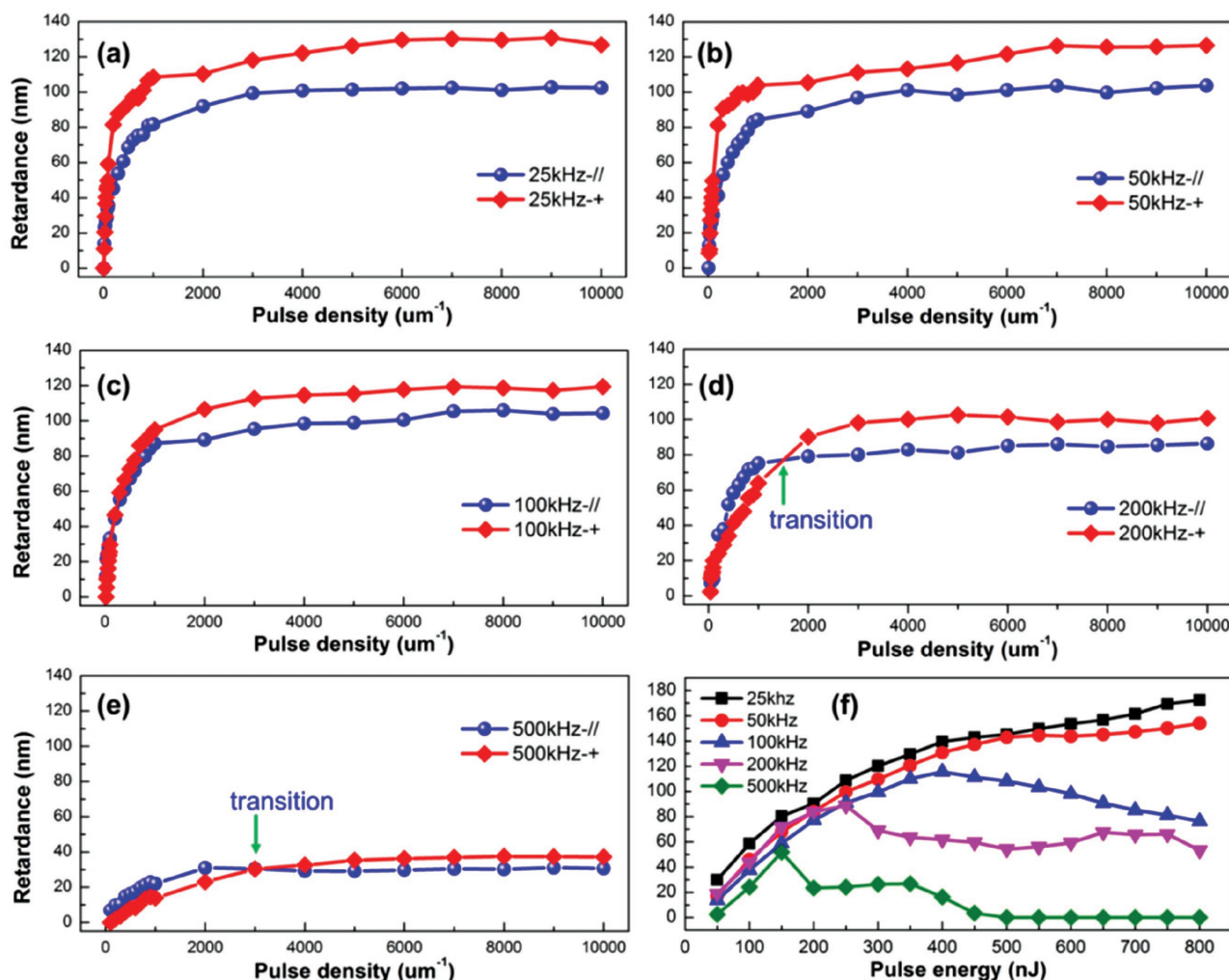


Figure 4. a–e) Dependence of laser induced retardance on pulse density at a fixed pulse energy of 0.25 μJ for various repetition rates in two polarization states and f) plots of retardance versus pulse energy at a fixed pulse density of 2500 pulse μm^{-1} for different repetition rates. Polarization direction: “//” for parallel, “+” for perpendicular to scanning direction.

A space variant polarization converter with the diameter of 1 mm that can generate optical vortices with radial and azimuthal polarizations was imprinted in GeO_2 glass with 600 fs pulses operating at 100 kHz. The characterization results of the fabricated converter are exhibited in Figure 5. The retardance image exhibits a relatively uniform distribution of retardance (Figure 5a) with an average value of $\approx 0.5\pi$ at 532 nm wavelength (Figure 5b), which corresponds to the quarter-wave plate value. The image of azimuth of slow axis (Figure 5c) indicates that the orientations of anisotropic microstructures are perfectly aligned along radius direction. The continuous transition of azimuth of slow axis is indicated by Figure 5d. To verify the presence of radial/azimuthal polarization, the converter was illuminated with a circularly polarized green beam and imaged under a microscope with linear polarizer (analyzer) inserted at the output. The propeller shape typical for the radial or azimuthal polarization was clearly observed (Figure 5e,f), confirming the fabrication of the radial polarization converter. This provides an alternative way to achieve radial or azimuthal polarized optical

vortices with a piece of femtosecond laser microengineered GeO_2 glass, simply by controlling the handedness of the incident circular polarization.

Another application based on the manipulation of slow axis of the induced form birefringence demonstrated here is a computer-generated geometric phase Fourier hologram (CGH), which can convert the initial Gaussian beam into the target intensity distribution. The logo of South China University of Technology (Figure 6b) was encoded into the eight-bit grayscale CGH element (Figure 6c) with 0.1 megapixel and pixel spacing of 3 μm generated using the adapted weighted Gerchberg–Saxton algorithm.^[38] The CGH was imprinted in GeO_2 glass with pulse energy of 80 nJ. The image of azimuth of slow axis orientation (Figure 6d) shows that the maximum relative continuous phase change of π between the two adjacent pixels was achieved. By using the setup shown in Figure 6a, the target image was reconstructed with a 532 nm laser, as displayed in Figure 6e. The relatively low resolution of the reconstructed image is mainly due to the slightly hygroscopic surface of the

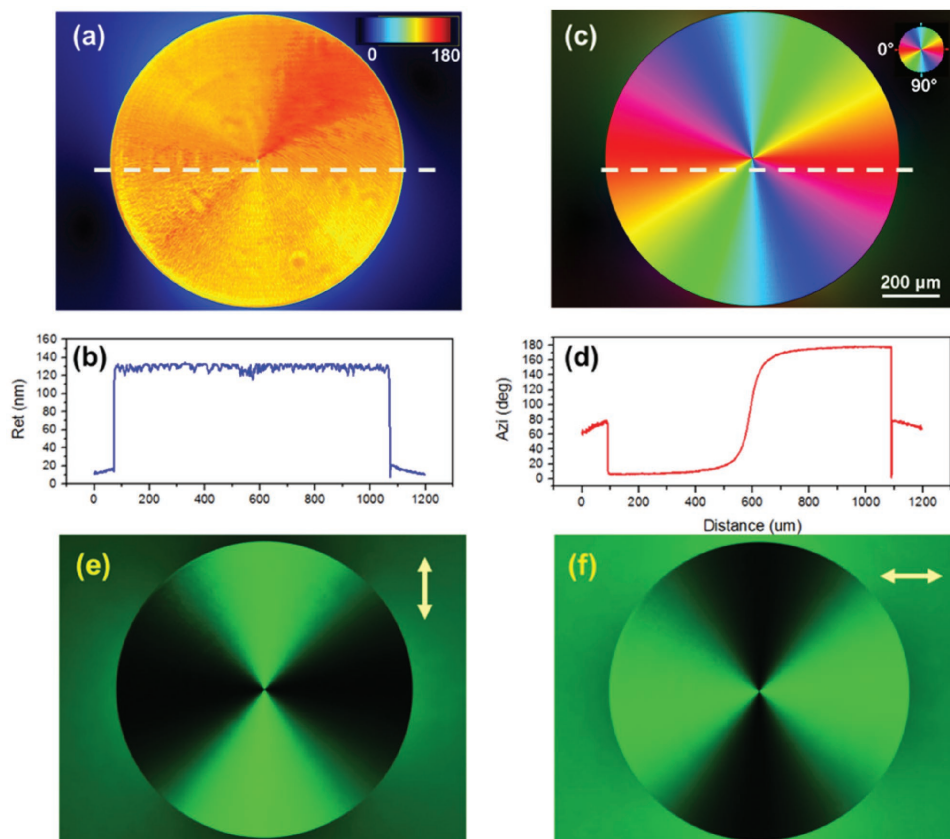


Figure 5. Radial and azimuthal polarization optical vortex converter (diameter of 1 mm) for circular incident polarization. a) Imaged retardance distribution of ≈ 130 nm and b) azimuth of slow axis orientation specifies imprinted element as a quarter wave plate working at wavelength of 532 nm. Pseudo colors indicate the direction of slow axis. c) Retardance and d) azimuth profiles measured along the white dashed line. e, f) Linearly polarized optical transmission images of polarization sensitive element illuminated by circularly polarized light.

sample, which can be significantly improved by surface polishing and coating. Moreover, this technique may extend the applications of GeO_2 glass in some new research fields.

3. Conclusions

In summary, form birefringence with polarization dependent slow axis induced by ultrafast laser pulses in GeO_2 glass is systematically investigated. We observed that the retardance induced by laser scanning is two times higher than that by stationary irradiation under similar conditions. The energy threshold of form birefringence formation exhibits a linear increase as a function of pulse duration. The favorable pulse energy for optimized retardance in GeO_2 glass is $\approx 65\%$ lower than in fused silica at 200 kHz. The optimum pulse duration for optimized retardance in GeO_2 glass lies within sub-picosecond region, i.e., typically around 500 fs, while in fused silica it is in the picosecond regime at around 1–2 ps. A reversed dependence of form birefringence on polarization direction, which is repetition rate related, is observed in GeO_2 glass. Two important optical applications including a polarization vortex converter and a computer generated hologram are successfully demonstrated in GeO_2 glass by manipulation of the induced form birefringence. The microengineering of optical properties

of GeO_2 glass by ultrafast laser direct-writing may lead to new applications of GeO_2 glass in photonics.

4. Experimental Section

Preparation of Sample: The GeO_2 glass sample was prepared from GeO_2 powder (99.999% purity), which was melted at 1600 °C in a platinum crucible for 2 h. The melt in the crucible was then cooled to room temperature in air. The formed glass was annealed at 500 °C for 3 h to release the residual stress. The prepared transparent bubble-free sample was polished for laser processing and further characterization. The sample was stored in a desiccator in between the experiments because of the hygroscopic properties of this glass. For comparison a commercially available UVSIL silica glass plate was used in the experiments.

Laser Processing and Characterization: The laser processing was carried out with a mode-locked regenerative amplified Yb:KGW-based femtosecond laser system (PHAROS, Light Conversion Ltd.), operating at a wavelength of 1030 nm with a pulse duration range from 300 fs to 10 ps and adjustable repetition rates from 1 to 500 kHz. Pulse energy was controlled by the combination of a half-wave plate and a Glan polarizer and measured after a 0.55 numerical aperture aspheric lens that focuses the beam into glass samples at a depth of about 100 μm below the sample surface. Another half-wave plate was inserted in the light path before the focusing lens for the control of the polarization orientation of the linearly polarized laser beam. The imprinted elements were optically visualized with an optical microscope and/or further characterized with the quantitative birefringence measurement system

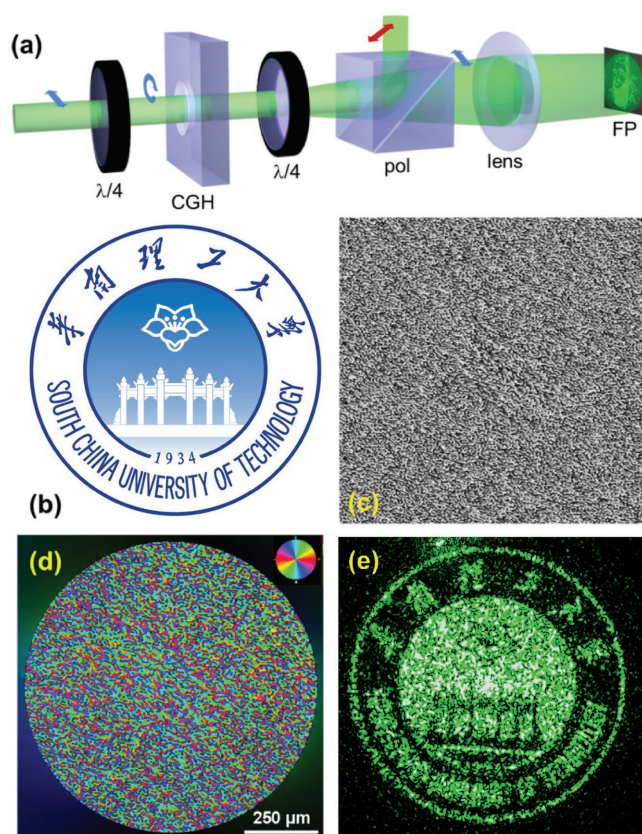


Figure 6. Computer-generated geometric phase Fourier hologram (CGH) imprinted in GeO_2 glass. a) Setup for polarization filtering and target image reconstruction. b) Original logo of South China University of Technology. c) Computer-generated geometric phase Fourier hologram of the portrait; d) Orientation of slow axis of the laser-imprinted CGH and e) the university logo reconstructed by the imprinted hologram illuminated with a 532 nm laser.

(CRi Abrio, Olympus BX51) operating at 546 nm wavelength, which allows measurement of the absolute value of the retardance and mapping of the slow axis orientation. An Nd:YAG continuous wave laser (Spectra-Physics) frequency-doubled to 532 nm was used to characterize the Gaussian beam propagation through the imprinted optical elements.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

form birefringence, GeO_2 glass, nanogratings, photonic applications, ultrafast lasers

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- [1] R. R. Gattass, E. Mazur, *Nat. Photonics* **2008**, *2*, 219.
- [2] D. Tan, K. N. Sharafudeen, Y. Yue, J. Qiu, *Prog. Mater. Sci.* **2016**, *76*, 154.
- [3] K. M. Davis, K. Miura, N. Sugimoto, K. Hirao, *Opt. Lett.* **1996**, *21*, 1729.
- [4] Y. Shimotsuma, P. G. Kazansky, J. Qiu, K. Hirao, *Phys. Rev. Lett.* **2003**, *91*, 247405.
- [5] E. N. Glezer, E. Mazur, *Appl. Phys. Lett.* **1997**, *71*, 882.
- [6] P. G. Kazansky, H. Inouye, T. Mitsuyu, K. Miura, J. Qiu, K. Hirao, F. Starrost, *Phys. Rev. Lett.* **1999**, *82*, 2199.
- [7] C. Hnatovsky, R. S. Taylor, E. Simova, V. R. Bhardwaj, D. M. Rayner, P. B. Corkum, *Opt. Lett.* **2005**, *30*, 1867.
- [8] R. Drevinskas, M. Gecevicius, M. Beresna, Y. Bellouard, P. G. Kazansky, *Opt. Express* **2015**, *23*, 1428.
- [9] E. Bricchi, P. G. Kazansky, *Appl. Phys. Lett.* **2006**, *88*, 111119.
- [10] K. Ke, E. F. Hasselbrink, A. J. Hunt, *Anal. Chem.* **2005**, *77*, 5083.
- [11] Y. Liao, J. Song, E. Li, Y. Luo, Y. Shen, D. Chen, Y. Cheng, Z. Xu, K. Sugioka, K. Midorikawa, *Lab Chip* **2012**, *12*, 746.
- [12] M. Beresna, M. Gecevicius, P. G. Kazansky, *Opt. Mater. Express* **2011**, *1*, 783.
- [13] Y. Shimotsuma, M. Sakakura, P. G. Kazansky, M. Beresna, J. Qiu, K. Miura, K. Hirao, *Adv. Mater.* **2010**, *22*, 4039.
- [14] J. Zhang, M. Gecevicius, M. Beresna, P. G. Kazansky, *Phys. Rev. Lett.* **2014**, *112*, 033901.
- [15] V. R. Bhardwaj, E. Simova, P. P. Rajeev, C. Hnatovsky, R. S. Taylor, D. M. Rayner, P. B. Corkum, *Phys. Rev. Lett.* **2006**, *96*, 057404.
- [16] A. Rudenko, J.-P. Colombier, T. E. Itina, *Phys. Rev. B* **2016**, *93*, 075427.
- [17] S. Richter, F. Jia, M. Heinrich, S. Doering, U. Peschel, A. Tuennermann, S. Nolte, *Opt. Lett.* **2012**, *37*, 482.
- [18] M. Beresna, M. Gecevicius, P. G. Kazansky, T. Taylor, A. V. Kavokin, *Appl. Phys. Lett.* **2012**, *101*, 053120.
- [19] Y. Shimotsuma, T. Asai, M. Sakakura, K. Miura, *J. Laser Micro/Nanoeng.* **2014**, *9*, 31.
- [20] F. Zhang, H. Zhang, G. Dong, J. Qiu, *J. Opt. Soc. Am. B* **2014**, *31*, 860.

- [21] T. Asai, Y. Shimotsuna, T. Kurita, A. Murata, S. Kubota, M. Sakakura, K. Miura, F. Brisset, B. Pommellec, M. Lancry, J. Ballato, *J. Am. Ceram. Soc.* **2015**, *98*, 1471.
- [22] S. Richter, C. Miese, S. Döring, F. Zimmermann, M. J. Withford, A. Tünnermann, S. Nolte, *Opt. Mater. Express* **2013**, *3*, 1161.
- [23] F. Zimmermann, A. Plech, S. Richter, A. Tünnermann, S. Nolte, *Appl. Phys. Lett.* **2014**, *104*, 211107.
- [24] J. Cao, L. Mazerolles, M. Lancry, D. Solas, F. Brisset, B. Pommellec, *Opt. Lett.* **2016**, *41*, 2739.
- [25] A. Cerkauskaitė, R. Drevinskas, A. O. Rybaltovskii, P. G. Kazansky, *Opt. Express* **2017**, *25*, 8011.
- [26] S. S. Fedotov, R. Drevinskas, S. V. Lotarev, A. S. Lipatiev, M. Beresna, A. Čerkauskaitė, V. N. Sigaev, P. G. Kazansky, *Appl. Phys. Lett.* **2016**, *108*, 071905.
- [27] M. Lancry, J. Canning, K. Cook, M. Heili, D. R. Neuville, B. Pommellec, *Opt. Mater. Express* **2016**, *6*, 321.
- [28] S. Sakaguchi, S. I. Todoroki, *Appl. Opt.* **1997**, *36*, 6809.
- [29] F. L. Galeener, J. C. Mikkelsen, R. H. Geils, W. J. Mosby, *Appl. Phys. Lett.* **1978**, *32*, 34.
- [30] S. Kanehira, J. H. Si, J. R. Qiu, K. Fujita, K. Hirao, *Nano Lett.* **2005**, *5*, 1591.
- [31] X. Hu, Y. Dai, L. Yang, J. Song, C. Zhu, J. Qiu, *J. Appl. Phys.* **2007**, *101*, 023112.
- [32] M. Gecevicius, M. Beresna, J. Zhang, W. Yang, H. Takebe, P. G. Kazansky, *Opt. Express* **2013**, *21*, 3959.
- [33] S. Richter, M. Heinrich, S. Döring, A. Tünnermann, S. Nolte, *Appl. Phys. A* **2011**, *104*, 503.
- [34] M. Lancry, F. Zimmerman, R. Desmarchelier, J. Tian, F. Brisset, S. Nolte, B. Pommellec, *Appl. Phys. B* **2016**, *122*, 1.
- [35] C. Corbari, A. Champion, M. Gecevicius, M. Beresna, Y. Bellouard, P. G. Kazansky, *Opt. Express* **2013**, *21*, 3946.
- [36] V. G. Niziev, A. V. Nesterov, *J. Phys. D: Appl. Phys.* **1999**, *32*, 1455.
- [37] R. Drevinskas, M. Beresna, J. Zhang, A. G. Kazanskii, P. G. Kazansky, *Adv. Opt. Mater.* **2017**, *5*, 1600575.
- [38] R. Di Leonardo, F. Ianni, G. Ruocco, *Opt. Express* **2007**, *15*, 1913.